



**QUEEN'S
UNIVERSITY
BELFAST**

Manual mapping of drumlins in synthetic landscapes to assess operator effectiveness

Hillier, J., Smith, M. J., Armugam, R., Barr, I. D., Boston, C., Clark, C. D., Ely, J., Frankl, A., Greenwood, S. L., Gosselin, L., Hättestrand, C., Hogan, K., Hughes, A. L. C., Livingstone, S. J., Lovell, H., McHenry, M., Muñoz, Y., Pellicer, X. M., Pellitero, R., ... Wooldridge, K. (2015). Manual mapping of drumlins in synthetic landscapes to assess operator effectiveness. *Journal of Maps*, 11(5), 719-729. <https://doi.org/10.1080/17445647.2014.957251>

Published in:
Journal of Maps

Document Version:
Peer reviewed version

Queen's University Belfast - Research Portal:
[Link to publication record in Queen's University Belfast Research Portal](#)

Publisher rights

Copyright 2014 J. K. Hillier.
This is an Accepted Manuscript of an article published in Journal of Maps on 18 Sept 2014, available online:
http://www.tandfonline.com/doi/full/10.1080/17445647.2014.957251#.VCUuz_IdWWU

General rights

Copyright for the publications made accessible via the Queen's University Belfast Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

The Research Portal is Queen's institutional repository that provides access to Queen's research output. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact openaccess@qub.ac.uk.

Manual mapping of drumlins in synthetic landscapes to assess operator effectiveness

Hillier¹, J. K., Smith², M. J., Armugam¹, R., Barr³, I., Boston⁴, C. M., Clark⁵, C. D., Ely⁵, J., Fankl⁶, A., Greenwood⁷, S. L., Gosselin⁸, L., Hätttestrand⁹, C., Hogan¹⁰, K., Hughes¹¹, A. L. C., Livingstone⁵, S. J., Lovell¹², H., McHenry¹³, M., Munoz¹⁴, Y., Pellicer¹⁵, X. M., Pellitero¹⁶, R., Robb¹⁷, C., Roberson¹⁸, S., Ruther¹⁹, D., Spagnolo¹⁶, M., Standell¹, M., Stokes²⁰, C. R., Storrar²⁰, R., Tate²¹, N. J., Wooldridge²², K.

¹Department of Geography, Loughborough University, LE11 3TU, UK.

²School of Geography, Geology and Environment, Kingston University, KT1 2EE, UK.

³School of Geography, Archaeology and Palaeoecology, Queen's University Belfast, BT7 1NN, UK

⁴Department of Geography, University of Portsmouth, Portsmouth, PO1 3HE, UK.

⁵Department of Geography, The University of Sheffield, Sheffield, S10 2TN, UK

⁶Department of Geography, Ghent University, Krijgslaan 281, S8 9000 Ghent, Belgium.

⁷Department of Geological Sciences, Stockholm University, 10691 Stockholm, Sweden.

⁸Departement of Geography, Université du Québec à Rimouski, G5L 3A1, Canada.

⁹Department of Physical Geography and Quaternary Geology, Stockholm University, SE-106 91, Stockholm.

¹⁰British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET UK.

¹¹Department of Earth Science, University of Bergen and Bjerknes Centre for Climate Research, Allegaten 41, Bergen 5007, Norway.

¹²School of Geography, Queen Mary University of London, London, E1 4NS

¹³School of Environmental Sciences, University of Ulster, Coleraine, BT52 1SA, UK

¹⁴Department of Earth and Atmospheric Sciences, University of Houston, Houston, Texas, USA.

¹⁵Geological Survey of Ireland, Beggars Bush Buildings, Haddington Road, Dublin 4.

¹⁶Scott Polar Research Institute, University of Cambridge, Cambridge CB2 1ER, UK

¹⁷Department of Geography & Environment, School of Geosciences, University of Aberdeen, St. Mary's Building, Elphinstone Road, Aberdeen, AB24 3UF.

¹⁸British Geological Survey, Colby House, Stranmillis Court, Belfast ,BT9 5BF

¹⁹SognHøgskulen i Sogn og Fjordane, Postboks 133, 6851 Sogndal.

²⁰Department of Geography, Durham University, Durham, DH1 3LE, UK

²¹Department of Geography, University of Leicester, Leicester, LE1 7RH

²² Department of Geographical & Life Sciences, Canterbury Christ Church University, North Holmes Road, Canterbury, Kent, CT1 1QU.

43 **Abstract**

44

45 Mapped topographic features are important for understanding processes that sculpt the
46 Earth's surface. This paper presents maps that are the primary product of an exercise that
47 brought together 27 researchers with an interest in landform mapping wherein the efficacy
48 and causes of variation in mapping were tested using novel synthetic DEMs containing
49 drumlins. The variation between interpreters (e.g., mapping philosophy, experience) and
50 across the study region (e.g., woodland prevalence) opens these factors up to assessment.
51 *A priori* known answers in the synthetics increase the number and strength of conclusions
52 that may be drawn with respect to a traditional comparative study. Initial results suggest that
53 overall detection rates are relatively low (34-40%), but reliability of mapping is higher (72-
54 86%). The maps form a reference dataset.

55

56 Keywords: Glacial landform, Synthetic, Drumlin, Mapping, DEM, Objective

57

58 **1. Introduction**

59

60 Mapping the location and distribution of topographic features on the Earth's surface has long
61 been considered an important means for developing an understanding of the processes that
62 formed them (e.g., Hollingsworth, 1931; Menard, 1959). Ever since photography has been
63 used to survey, there has been a requirement to identify features within an image. Aerial
64 photography facilitated the holistic visualisation of features within the landscape and made
65 photo interpretation a key tool for academic study. However, it was the military exploitation of
66 aerial imagery that drove early development in its interpretation (e.g., Anonymous, 1963;
67 Colwell, 1960), which was later mirrored in the photogrammetric literature (e.g., Thompson,
68 1966).

69

70 It is against this cultural backdrop of image interpretation that Earth scientists developed
71 qualitative methodologies for mapping landforms; techniques initially used in aerial

72 photography (e.g., Prest et al., 1968) were transferred to satellite imagery (e.g., Punkari,
73 1980) and then digital elevation models (DEMs; e.g., Evans, 1972; Smith and Clark, 2005).
74 The advent of computers and digital spatial data led to the development of algorithms for the
75 automated identification of landforms (e.g., Behn et al., 2004; Hillier and Watts, 2004; Bue
76 and Stepinski, 2006). Some landforms offer quantitatively distinct boundaries that make their
77 identification relatively simple, for example determining flow paths for river channels using
78 DEMs (e.g., van Asselen and Seijmonsbergen, 2006). However the boundaries of many
79 landforms are poorly defined (e.g., Fisher et al., 2004; Evans, 2012), requiring complex
80 visual and analytical heuristics for landform identification. This has also made automated
81 identification a non-trivial task and it is only in the last decade that significant progress has
82 been made (e.g., Drăguț and Blaschke, 2006; Hillier, 2008; Anders et al, 2011). Even then,
83 anecdotal observation of researchers' preferences and its usage in publications suggests
84 that manual interpretation is generally still considered to be more reliable.

85
86 If manual interpretative techniques are preferred for some mapping activities it is important to
87 assess the levels of accuracy and precision that are attainable. However, this is difficult as it
88 is not possible to know *a priori* the actual number of features in a landscape or their 'true'
89 boundaries. It is possible to determine a control, a sub-area within a study, within which
90 interpreters map features that can later be compared with mapping completed for a whole
91 study (e.g., Smith and Clark, 2005). Likewise, it is also possible to compare the mapping of
92 different interpreters to ascertain if there are significant differences between individuals (e.g.,
93 Podwysocki et al, 1975; Siegal, 1977). This work suggests that variation in mapping by a
94 single interpreter can be relatively low (Smith and Clark, 2005), but that variation between
95 interpreters can be high. The absolute, as opposed to relative, accuracies however still
96 require investigation.

97
98 The purpose of geomorphological mapping is typically to produce quantitative, repeatable,
99 observations of features in the landscape, but to what extent can subjective manual
100 interpretations be reproducible? What is the achievable accuracy of subjective mapping?

101 What is the variation in accuracy and which characteristics of the interpreter and landscape
102 govern any variation? Are there any systematic biases in the mapping, and how do these
103 relate to the definition of the feature's boundary being used in practice? These are important
104 questions to understand when making inferences from data and should guide the
105 development of clear and consistent methodologies for interpretative mapping, yet their
106 investigation is difficult without *a priori* knowledge of landscapes and the variability between
107 both interpreters and the landforms they map. Synthetic DEMs (e.g., Hillier and Smith, 2012),
108 on the other hand, are designed terrains within which key components are known *a priori*,
109 and so they have facilitated some progress on these and related questions. Specifically,
110 synthetic DEMs were used to determine an optimal semi-automated method for drumlin
111 extraction (Hillier and Smith, 2014) and to assess multi-resolution segmentation algorithms
112 for delimiting drumlins (Eisank et al, 2014). In addition, a pilot study on manual mapping
113 tentatively indicated that drumlin amplitude may be the key dimension governing drumlin
114 detectability (Fig. 1c) (Arumgam et al., 2012).

115

116 This paper and the accompanying maps present the outcomes of an exercise that brought
117 together a variety of researchers with an interest in landform mapping where the efficacy and
118 variation of interpretation between individuals was tested using synthetic DEMs. Initial
119 findings from this work are presented, and the maps form a reference dataset for future work.

120

121 **2. Methods**

122

123 **2.1 Research Design**

124

125 In order to test aspects of interpreter mapping, such as 'completeness' (defined below), it is
126 necessary to know with certainty exactly which landforms exist in a landscape and where
127 they are, but for incompletely defined landforms in a real landscape this is unknowable.
128 Thus, a sufficiently realistic DEM containing an *a priori* known answer is required to give
129 these absolute measures of effectiveness (see 'Results'), which traditional mapper inter-

130 comparisons simply cannot provide or estimate. One way to generate this might be to use a
131 'landscape evolution model' (e.g., Chase, 1992; Braun and Sambridge, 1997) to generate an
132 artificial landscape that is both realistic and statistically comparable to a real landscape
133 including all factors such as vegetation and anthropogenic alteration, but this has not yet
134 been achieved for glacial bedforms. Hillier and Smith (2012) therefore proposed an
135 alternative hybrid method. They used an existing DEM of real terrain and inserted synthetic
136 landforms of known size and shape into it. The locations and orientations of the landforms
137 are set differently for each synthetic DEM. Synthetic DEMs created in this way make it
138 possible to assess the ability of interpreters to identify landforms in an absolute sense,
139 something that is not possible with a real landscape. Any number of synthetic variants of a
140 landscape can be produced for interpreters can map. Then, comparing and contrasting the
141 mapped outputs allows conclusions to be drawn that include quantitative error estimates
142 about properties such as absolute accuracy, variability, repeatability, and systematic biases.
143 Thus, subject to establishing the representativeness of the synthetic DEMs used in each
144 case study, this increases the number and strength of conclusions that may be drawn with
145 respect to a traditional comparative study. An experimental approach employing synthetic
146 DEMs is used here. These currently insert only one landform type (i.e., drumlins), however
147 this is sufficient to support the aims of the paper and there is no reason why more complex
148 synthetics could not be constructed in the future.

149

150 **2.2 Choice of landform**

151

152 For this work drumlins were selected as the landform to be mapped. Drumlins are elongate
153 hills, typically 100s m long and up to a few 10s of metres high (Menzies, 1979; Wellner,
154 2001; Smith et al., 2007; Clark et al, 2009; Spagnolo et al, 2012; Hillier and Smith, 2014).
155 They are very likely formed subglacially, parallel to ice flow (Smith et al, 2007; King et al,
156 2009; Johnson et al, 2010), and, as they can persist in the landscape, they encode
157 information on the location and direction of flow of former ice cover (e.g., Hollingsworth,
158 1931; Kleman and Borgström, 1996; Finlayson et al, 2010) and perhaps even the nature and

159 velocity of ice flow (e.g., Colgan and Mickelson, 1997; Smalley et al, 2000; Stokes and Clark,
160 2002). Such information is valuable for understanding the histories of past ice-sheet change.
161 Thus, they are of scientific interest. Commonly, drumlins are mapped manually, often by an
162 individual interpreter (e.g., Hughes, et al, 2010). However, their exact form has not yet been
163 definitively, robustly and quantitatively defined and so a drumlin's spatial footprint is open to
164 interpretation and differs between interpreters (see e.g., Fig 1a of Hillier and Smith, 2014).
165 Despite this there has been some limited success in the use of automated algorithms to map
166 drumlins (e.g., Saha et al, 2011). As such, drumlins seem likely to be able to be mapped
167 accurately, reproducibly and objectively, and are regularly interpreted upon this basis, yet
168 making this operational remains a challenge.

169

170 **2.3 Generation of Synthetic Landscapes**

171

172 In order to generate synthetic DEMs using the method of Hillier and Smith (2012), a 'donor'
173 DEM is required. This study uses the NEXMap® Britain DEM, which is an interferometric
174 synthetic aperture radar (IfSAR) product with a spatial resolution of 5 m and vertical accuracy
175 of ~0.5-1 m (Intermap, 2004). Once the DEM is selected it is then necessary to manually
176 identify the drumlins present. In this case the identification is that done by Smith et al (2006)
177 (Fig. 1b), who used different visualisations of the landscape (i.e., relief shaded in two
178 orthogonal directions, gradient, curvature, local contrast stretch). This mapping approach
179 was employed by Smith et al (2006) on multiple occasions in order to both check the
180 repeatability of the mapping and to reduce bias that may have been introduced in any one
181 session. The mapping stage serves two purposes: (1) to parameterise the synthetic drumlins
182 to be inserted in to the DEM, and (2), to allow the removal of the original drumlins.

183

184 The population of originally mapped drumlins were parameterised in terms of their shape
185 (i.e., Gaussian) and dimensions - height (H), width (W), and length (L). These were then
186 used to generate a set of synthetic, idealised, drumlins; each mapped drumlin created one
187 synthetic drumlin, which retained the same identification number and parameter triplet (H , W ,

188 *L*) wherever it was placed. Visually selected median filters (see Hillier and Smith, 2014) were
189 used to quantify and remove the original drumlins. The synthetic features were then
190 randomly inserted in a non-overlapping fashion back into the DEM, which also preserved
191 their spatial density and the distribution of their orientations. These measures are sufficient
192 to ensure that errors associated with recovery of *H*, *L* and *W* are the same in the synthetics
193 as the original landscape, at least for semi-automated techniques (Hillier and Smith, 2012).
194 This, combined with the use of a real DEM, ensured that the synthetics were statistically
195 representative of the real landscape. Full details of the procedure are outlined in Hillier and
196 Smith (2012). It was intended that drumlin-shaped landforms were equally as difficult to find
197 in the synthetics as they are in reality. The perfect Gaussian shape of the synthetics and their
198 ability to cut across landscape features in an unnatural way may tend to act to make them
199 easier to identify. Conversely, their lack of alignment with each other may make them more
200 difficult to find than natural drumlins. The lack of local parallel alignment was highlighted as
201 a disadvantage during the workshop. As a result, five additional DEMs were created wherein
202 drumlins were aligned perpendicular to the original flow field, which also avoids confusion
203 with any incompletely removed glacial texture in the DEM. If anything, these synthetic DEMs
204 including parallel alignment represent a limiting best case for drumlin detection. None of the
205 synthetics used include parabolic, ovoid or crosscutting drumlins (e.g., Rose and Letzer,
206 1977; Shaw, 1983; Shaw and Kavill, 1989; Hillier and Smith, 2008; Boyce and Eyles, 1991;
207 MacLachlan and Eyles, 2013), which could complicate mapping.

208

209 **2.4 Study Area**

210

211 This work used the same study area as Hillier and Smith (2012) (Fig. 1a), which has been
212 mapped in detail by other researchers studying the glacial geomorphology of the region (e.g.,
213 Rose and Letzer, 1975, 1977; Smith et al, 2006; Rose and Smith, 2008; Finlayson et al,
214 2010; Hughes et al., 2010). This area of Scotland sits between the Grampian Highlands to
215 the north and the Southern Uplands to the south and was glaciated during the Last Glacial
216 Maximum (LGM) and Younger Dryas (YD). It contains two identifiable suites of features

217 interpreted as "classically shaped" drumlins, namely of approximately leminscate or elliptical
218 footprints (e.g., Chorley, 1959; Reed, 1962). The drumlins mark the presence of flowing ice
219 during these time periods, broadly west to east during the LGM and north to south during the
220 YD. Drumlin dimensions are broadly comparable to those of other drumlins in the UK (Hillier
221 and Smith, 2014). The study area is similar to many previously glaciated regions of the UK in
222 that it contains topographic complexity in the form of regional relief (e.g., hills; Hillier and
223 Smith, 2008) and non-glacial anthropogenic 'clutter' (e.g., trees, houses; Sithole and
224 Vosselman, 2004), which vary in their amplitude and spatial density, respectively; it is
225 intended that these variations across the study area will allow their impacts upon mapping to
226 be isolated.

227

228 **2.5 Interpretive Mapping**

229

230 In order to test the variability of interpretive mapping individual researchers were invited to
231 map drumlins in the synthetic DEMs. There were a total of 27 respondents who had a range
232 of experiences and expertise within geomorphology, glaciology, Earth science and remote
233 sensing. They included undergraduate and postgraduate students, faculty and post-doctoral
234 researchers from a range of countries and of different nationalities, although all from Europe
235 or North America with a bias towards the United Kingdom.

236

237 In addition, whilst this manuscript and its associated maps present the outputs of this
238 mapping, a workshop was organised in order to present the draft results to participants and
239 to drive discussion. The ultimate goal of the project is to highlight the nature of differences
240 between interpreters and to begin the development of objective criteria for mapping. In total
241 25 people completed mapping for the project, with an overlapping set of 24 participants who
242 attended the workshop.

243

244 Interpreters were supplied with five raw synthetic DEMs and guidelines clearly stating that
245 each DEM contained exactly 173 drumlins, creating a total dataset of 865 landforms.

246 Interpreters were requested to prepare the DEMs for mapping using their software of choice
247 and whilst there was an assumption that relief shading, gradient and curvature (Smith and
248 Clark, 2005) may be prominent visualisation techniques, they were not restricted in the use
249 of any particular manipulation. In order to generate a statistically significant number of results
250 interpreters were requested to map:

- 251 • drumlin outlines for each DEM using their preferred or 'best' visualisation
- 252 • separate sets of outlines individually using each of the relief shaded, gradient and
253 curvature visualisation for two randomly selected DEMs
- 254 • mapping of drumlin ridge crests and high points for two randomly selected DEMs
255 using their 'best' method.

256

257 Mapping results were returned as individual shapefiles and a questionnaire completed,
258 qualitatively surveying individual approaches to mapping. Synthetic drumlins were,
259 simplistically, considered to be 'found' if their centre points lay within a digitised outline; when
260 multiple synthetics were encompassed, the closest to the digitised outline's centre was
261 selected. Subsequently, all mapped polygons (outlines, ridges, centre points) within
262 shapefiles were re-numbered so their ID numbers matched those of the relevant synthetic
263 drumlin. Thus, the behaviour of each drumlin's *H*, *W*, *L* triplet can be compared between
264 interpreters, DEMs and visualisations.

265

266 **3. Results**

267

268 The five main synthetic DEMs were mapped by 25 interpreters giving a total of 21,625
269 drumlins to be identified by the group. 12,121 outlines were mapped in interpreters' preferred
270 visualisations, 8,667 of which were coincident with the original synthetic drumlins. Table 1
271 presents an error matrix in the standard format used in remote sensing (e.g., Lillesand et al,
272 2008) reporting these results. For accessibility, the equivalent terminology from information
273 retrieval theory is also given (e.g., Manning et al, 2008). The matrix shows that whilst the
274 'overall accuracy' is relatively low (8667/25,079) at 34%, the producer's accuracy, 'reliability'

275 or 'precision' (8,667/12,121) is relatively high at 72% (i.e., few false positives). This reflects
 276 the conservative number of drumlins generally mapped, but the high confidence in their
 277 accuracy. As a result, the user's accuracy, 'completeness', or 'recall' is also relatively low at
 278 40% (8,667/21,625). Figure 2 shows the number of drumlins mapped by individual
 279 interpreters across all five DEMs; there is some variability in the totals mapped which is likely
 280 dependent upon the visualisation method and mapping philosophy employed by the
 281 individual. However, the number of correct drumlins is much more stable, typically between
 282 300 and 500 landforms with a mean of 347 and standard deviation of 97.

284 To supplement the main mapping, 12 interpreters mapped one of four additional synthetic
 285 DEMs containing parallel alignment, a total of 2076 drumlins. Fig. 2 shows numbers scaled
 286 (x5) to allow comparison with the main mapping. The number of correctly mapped drumlins
 287 likely increases a little (t-test, unequal variance, $p=0.11$) for these DEMs to 402 with a
 288 standard deviation of 82, with the variability likely arising for similar reasons to that in maps
 289 1-5. The increase in correctly mapped drumlins is driven by a moderately sized but notable
 290 increase in 'reliability' (885/1028) to 86%, leaving 'completeness' (885/2076) at the slightly
 291 raised level of 43% and 'overall accuracy' (885/2219) up to 40%, both still relatively low.
 292 Thus, mappers are able to make some use of parallel alignment although perhaps less than
 293 expected from the strength of feeling about this at the workshop. Idealised drumlin shapes
 294 combined with parallel alignment, especially when using a necessarily smoothed (2 km mean
 295 filter) flow field, arguably represents a best case scenario for detection.

297 **Table 1:** Error Matrix showing the number of correctly mapped drumlins in addition to errors
 298 of omission and commission. See text for an interpretation of the matrix. Figures for DEMs
 299 containing parallel alignment are given in brackets.

| | Mapped | Not Mapped 'omission' | Total |
|---------------------------|----------------------------------|--|-----------------|
| Correct | 8667 (885) [True positive] | 12958 (1191) [False negative, Type II error] | 21625 (2076) |
| Incorrect (commission) | 3454 (143) | | 3454 |

| | | | |
|--|-----------------------------------|-----------------|-----------------|
| | [False positive, Type I error] | | (143) |
| | 12121 (1028) | 12958 (1191) | 25079 (2219) |

300
301

302 The maps present the outcomes of mapping from each of the individual interpreter's
303 digitisation of drumlin outlines using their 'best' attempt based upon their preferred
304 visualisation. Each of the five synthetic DEMs (Maps 1-5) is presented separately as part of
305 an interactive PDF, as are the DEMs containing parallel conformity (Maps 6-9). The PDF is
306 designed to be a digital product that the reader interacts with; map layers within the PDF can
307 be turned on and off allowing the original synthetic drumlins to be viewed, along with
308 mapping by each of the interpreters. This allows direct comparison by switching between
309 layers. The underlying topography is displayed as relief-shaded terrain illuminated from 315°.
310 Additionally there are **two** layers that display the outlines of the synthetic drumlins: (1) the
311 'Number of Times Identified' layer shows the frequency with which the drumlin was correctly
312 identified and (2) the 'Height' layer shows the amplitude of the drumlin classified using a
313 Jenk's Natural Breaks algorithm.

314

315 4. Conclusions

316

317 Manual mapping of landforms from remotely sensed imagery remains a common task in the
318 Earth sciences because it both seems effective and is practical to implement. In contrast,
319 whilst automated and semi-automated detection methods have significantly improved, they
320 remain difficult to implement and are of variable quality. Yet the objectiveness and
321 repeatability of manual interpretation can be questioned. Testing the efficacy of mapping in
322 an absolute sense is difficult as it is not possible to know, *a priori*, the landforms that actually
323 exist in the landscape.

324

325 To this end, this work utilises innovative synthetic landscapes. The current process takes a
326 DEM, removes existing landforms (specifically drumlins) and then uses the metrics from this
327 landform population to parameterise a new idealised set that are inserted back in to the
328 model DEM. Five variations of this landscape were generated and 25 interpreters with
329 varying ability, experience, preferences, and time available mapped the drumlins within them.
330 This provides a first assessment of mapper capabilities with respect to a known baseline.
331 Each individual interpreter's mapped boundaries are overlaid on the DEMs and presented
332 within the maps accompanying this manuscript. As such, the maps form a reference dataset.
333 Initial results suggest that overall detection rates are relatively low, but reliability of mapping
334 can be high.

335

336 **Acknowledgements**

337

338 The European Geophysical Union financially supported the workshop including the provision
339 of travel grants to young researchers. Loughborough University and the CHES group in the
340 Geography Department provided financial support and facilities for the workshop. Kathy
341 Mather's quantitative MSc work, co-supervised by N. Woodcock, on drumlin morphology
342 (Mather, 2008) acted as an early driver for this project. The NEXTMap DEM data were
343 supplied to MS.

344

345 **Software**

346

347 Esri ArcGIS 10 was used for the production of the accompanying maps, with many of the
348 individual mappers also using it to digitise the outlines of the synthetic drumlins. GMT
349 (Wessel and Smith, 1998) was used for the underlying analysis; e.g., DEM production,
350 outline renumbering.

351

352 **Map Design**

353

354 The accompanying atlas was designed as an interactive document that the reader can
355 explore. It represents the output from the first ever attempt to objectively compare mapping
356 of landforms by individual interpreters. An A1 page size was selected in order to maximise
357 the resolution of the underlying raster topography, which is presented as a Swiss-type
358 hillshade. **Each** map has a unique underlying DEM, varying according to where the synthetic
359 drumlins are. Ancillary elements surround the map providing location, scale, title and
360 legends. Palatino was selected for typography as a readable, "classic", style typeface.

361

362 The key part of the maps is the interactive layers; with the layer tab visible each layer within
363 each page is visible. Any of these elements can have their visibility toggled on or off. There
364 are three primary layers under "Main Map". "Mapping" shows all mapping of the individual
365 interpreters; this whole layer, or individual sub-layers, can have their visibility toggled. "Times
366 Identified" shows the actual synthetic drumlins and is symbolised based upon the number of
367 times they were identified. "Drumlin Height (m)" is symbolised to show the amplitude of the
368 synthetic drumlins and is specifically included to emphasise the link with the number of times
369 forms were identified; compare this to Fig. 1c.

370

371 **References**

372

373 Anders, N.S., Seijmonsbergen, A.C., Bouten, W., 2011. Segmentation optimization and
374 stratified object-based analysis for semi-automated geomorphological mapping. *Remote*
375 *Sensing of Environment* 115, 2976-2985.

376

377 Anonymous, 1963. Imagery interpretation section - the eyes of the division. US Army, 24th
378 Infantry Division, Augsburg, Germany.

379

380 Armugam, R., Hillier, J. K., Smith, M., 2012. Quantifying how well drumlins can be mapped
381 using synthetic DEMs. IAG/AIG International Workshop: 'Objective Geomorphological
382 Representation Models: Breaking Through a New Geomorphological Mapping Frontier'.
383 University of Salerno, Oct 15-19.

384

385 Behn, M. D., Sinton, J. M., Deitrick, R. S., 2004. Effect of the Galapagos hotspot on
386 seamount volcanism along the Galapagos Spreading Center. *Earth and Planetary Science*
387 *Letters*, 217, 331-347.

388

389 Boyce, J., and Eyles, N., 1991. Drumlins carved by deforming till streams below the
390 Laurentide ice sheet. *Geology*, 19(8), 787-790.

391

392 Braun, J., Sambridge, M., 1997. Modelling landscape evolution on geological time scales: a
 393 new method based on irregular spatial discretization. *Basin Research* 9, 27–52.
 394
 395 Bue, B. D., and T. F. Stepinski, 2006. Automated classification of landforms on Mars,
 396 *Comput. Geosci.*, 32(5), 604–614, doi:10.1016/j.cageo.2005.09.004.
 397
 398 Chase, C.G., 1992. Fluvial landscupting and the fractal dimension of topography.
 399 *Geomorphology* 5, 39–57.
 400
 401 Chorley, R. J., 1959. The Shape of drumlins. *J. Glaciology*, 3, 339–344.
 402
 403 Clark, C.D., Hughes, A.L.C., Greenwood, S.L., Spagnolo, M., Ng, F.S.L., 2009. Size and
 404 shape characteristics of drumlins, derived from a large sample, and associated scaling laws.
 405 *Quaternary Science Reviews* 28, 677-692.
 406
 407 Colgan, P., Mickelson, D. M. (1997). Genesis of streamlined landforms and flow history of
 408 the Green Bay Lobe, Wisconsin, USA. *Sediment. Geol.*, 111, 7-25.
 409
 410 Colwell, R.N. (Ed.), 1960. *Manual of Photographic Intrerpretation*, American Society of
 411 Photogrammetry, pp868.
 412
 413 Drăguț, L., Blaschke, T., 2006. Automated classification of landform elements using
 414 object-based image analysis. *Geomorphology* 81, 330–344.
 415
 416 Eisank, C., Smith, M., Hillier, J. 2014. Assessment of multiresolution segmentation for
 417 delimiting drumlins in digital elevation models. *Geomorphology*, 214, 452-464.
 418
 419 Evans, I.S., 1972. General Geomorphometry, derivatives of altitude and descriptive
 420 statistics., In: Chorley, R.J. (Ed.), *Spatial Analysis in Geomorphology*. Harper and Row, New
 421 York, pp. 17-90.
 422
 423 Evans, I. S., 2012. Geomorphometry and landform mapping: What is a landform?
 424 *Geomorphology*, 137, 94-106. doi:10.1016/j.geomorph.2010.09.029
 425
 426 Finlayson, A., Merritt, J., Browne, M., Merritt, J., McMillan, A., Whitbred, K., 2010. Ice sheet
 427 advance, dynamics, and decay configurations: evidence from west central Scotland.
 428 *Quaternary Science Reviews*, 29 (7-8), 969-988.
 429
 430 Fisher, P., Wood, J., Cheng, T., 2004. Where is Helvellyn? Fuzziness of multi-scale
 431 landscape morphometry. *Transactions of the Institute of British Geographers* 29, 106–128.
 432
 433 Hillier, J. K., Watts, A. B., 2004. “Plate-like” subsidence of the East Pacific Rise - South
 434 Pacific Superswell system. *Journal of Geophysical Research*, 109(B10102).
 435
 436 Hillier, J. K., 2008. Seamount detection and isolation with a modified wavelet transform.
 437 *Basin Research*, 20, 555-573.
 438
 439 Hillier, J. K., Smith, M. 2008. Residual relief separation: digital elevation model enhancement
 440 for geomorphological mapping. *Earth Surface Processes and Landforms*, 33(14), 2266–
 441 2276. doi:10.1002/esp.

- Hillier, J.K., Smith, M.J., 2012. Testing 3D landform quantification methods with synthetic drumlins in a real digital elevation model *Geomorphology* 153-154, 61-73.
- Hillier, J.K., Smith, M.J., 2014. Testing techniques to quantify drumlin height and volume; synthetic DEMs as a diagnostic tool. *Earth Surface Processes and Landforms*, 39(5), 676-688, doi:10.1002/esp.3530.
- Hollingsworth, S. E. 1931. The glaciation of western Edenside and adjoining areas and the drumlins of Edenside and the Solway basin. *Quart. J. Geol. Soc. London*, 87(2), 281-359.
- Hughes, A.L.C., Clark, C.D., Jordan, C.J., 2010. Subglacial bedforms of the last British Ice Sheet. *Journal of Maps* 6, 543-563.
- Intermap, 2004. Intermap Product Handbook and Quickstart Guide (v3.3). Intermap, Englewood, California.
- Johnson, M. D., Schomacker, A., Benediktsson, I. O., Geiger, A. J., Ferguson, A., & Ingolfsson, O., 2010. Active drumlin field revealed at the margin of Mulajokull, Iceland: A surge-type glacier. *Geology*, 38(10), 943–946. doi:10.1130/G31371.1
- Kleman, J., Borgström, I., 1996. Reconstruction of palaeo-ice sheets: the use of geomorphological data. *Earth Surface Processes and Landforms* 21, 893-909.
- King, E. C., Hindmarsh, R. C. A., and Stokes, C. R., 2009. Formation of mega-scale glacial lineations observed beneath a west Antarctic ice stream. *Nat. Geosci.*, 2, 585–596.
- Lillesand, T.M., Kiefer, R.W., Chipman, J.W., 2008. Remote sensing and image interpretation. John Wiley and Sons, New York.
- MacLachlan, J. C., and Eyles, C., 2013. Quantitative geomorphological analysis of drumlins in the Peterborough drumlin field, Ontario, Canada. *Geografiska Annaler: Series A, Physical Geography*, 95(2), 125–144.
- Manning, C. D., Raghavan, P., Schutze, H. 2008. Introduction to information retrieval. Cambridge University Press, Cambridge, UK. pp496. ISBN: [0521865719](#).
- Mather, K., 2008. Drumlins in the Howgills. MSc Dissertation. University of Cambridge.
- Menard, H. W., 1959. Geology of the Pacific sea floor. *Experientia*, 15, 205-244.
- Menzies, J., 1979. A review of the literature on the formation and location of drumlins. *Earth Science Reviews* 14, 315-359.
- Podwysocki, M.H., Moik, J.G., Shoup, W.C., 1975. Quantification of geologic lineaments by manual and machine processing techniques, Proceedings of the NASA Earth Resources Survey Symposium. NASA, Greenbelt, Maryland, pp. 885-905.
- Prest, V.K., Grant, D.R., Rampton, V.N., 1968. The Glacial Map of Canada, 1253A ed. Geological Survey of Canada.

493 Punkari, M., 1980. The ice lobes of the Scandinavian ice sheet during the deglaciation of
 494 Finland. *Boreas* 9, 307-310.

495

496 Reed, B., Galvin, C. J., and Millier, J. P., 1962. Some aspects of drumlin geometry. *American*
 497 *Journal of Science*, 260, 200–210.

498

499 Rose, J., Letzer, J. M., 1975. Drumlin measurements: a test of the reliability of data derived
 500 from 1:25,000 scale topographic maps, *Geol. Mag.*, 112, 361–371.

501

502 Rose, J., Letzer, J. M., 1977. Superimposed drumlins, *J. Glaciol.*, 18, 471–480.

503

504 Rose, J., Smith, M.J., 2008. Glacial geomorphological maps of the Glasgow region, western
 505 central Scotland. *Journal of Maps* v2008, 399-416.

506

507 Saha, K., Wells, N.A., Munro-Stasiuk, M., 2011. An object-oriented approach to automated
 508 landform mapping: A case study of drumlins. *Computers and Geosciences* 37, 1324-1336.

509

510 Shaw, J., 1983. Drumlin formation related to inverted melt-water erosional marks. *J.*
 511 *Glaciology*, 29(103), 461–479.

512

513 Shaw, J., Kvill, D., and Rains, B., 1989. Drumlins and catastrophic subglacial floods.
 514 *Sedimentary Geology*, 62(2), 177–202.

515

516 Siegal, B.S., 1977. Significance of operator variation and the angle of illumination in
 517 lineament analysis of synoptic images. *Modern Geology* 6, 75-85.

518

519 Sithole, G., and Vosselman, G., 2004. Experimental comparison of filter algorithms for bare-
 520 Earth extraction from airborne laser scanning point clouds. *ISPRS Journal of*
 521 *Photogrammetry & Remote Sensing*, 59, 85–101.

522

523 Smalley, I., Lu, P., Jefferson, I., 2000. The Golf-Ball Model and the Purpose of Drumlin
 524 Formation. *Studia Quaternaria*, 17, 29-33.

525

526 Smith, A.M., Murray, T., Nicholls, K.W., Makinson, K., Adalgerirsdottir, G., Behar, A.E.,
 527 Vaughan, D.G., 2007. Rapid erosion, drumlin formation, and changing hydrology beneath an
 528 Antarctic Ice Stream. *Geology*, 35, 2, 127-130.

529

530 Smith, M.J., Clark, C.D., 2005. Methods for the visualisation of digital elevation models for
 531 landform mapping. *Earth Surface Processes and Landforms* 30, 885-900.

532

533 Smith, M.J., Rose, J., Booth, S., 2006. Geomorphological mapping of glacial landforms from
 534 remotely sensed data: an evaluation of the principal data sources and an assessment of their
 535 quality, *Geomorphology*, 76, 148–165.

536

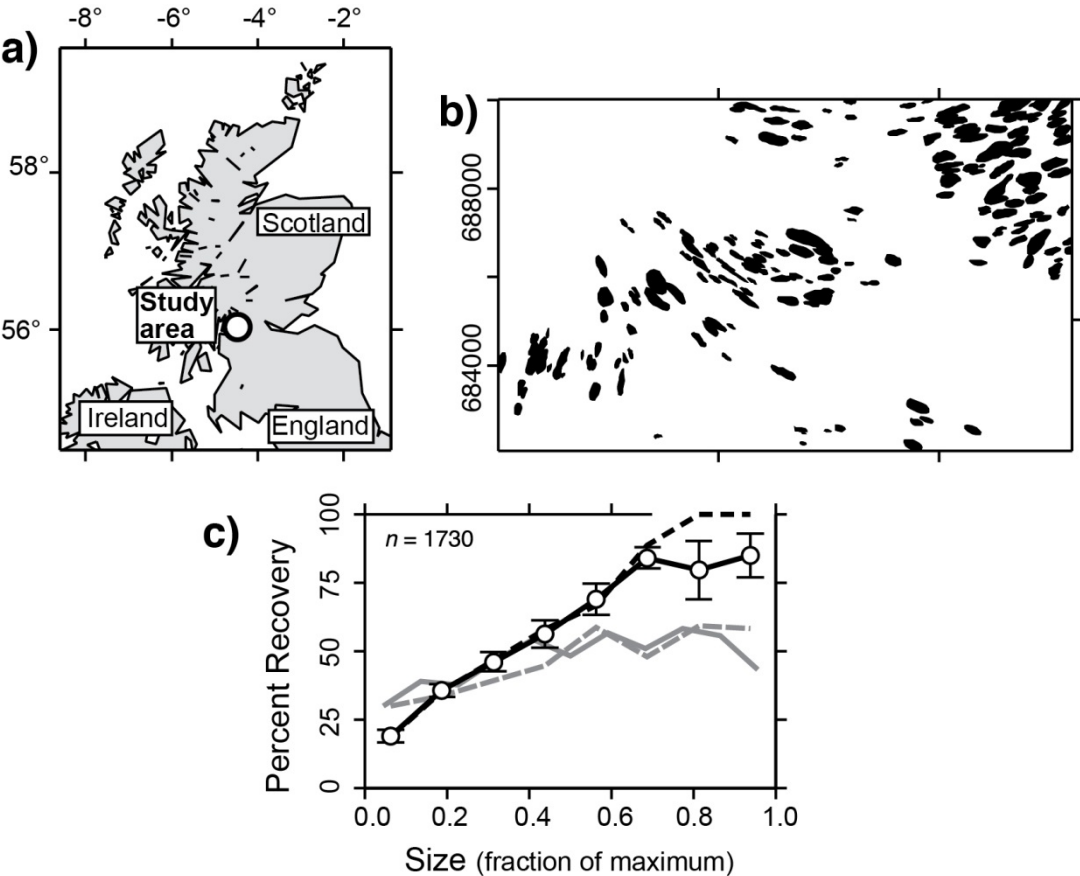
537 Spagnolo, M., Clark, C. D., & Hughes, A. L. C., 2012. Drumlin relief. *Geomorphology*, 153-
 538 154, 179–191.

539

540 Stokes, C. R., Clark, C. D., 2002. Are long subglacial bedforms indicative of fast ice flow?
 541 *Boreas*, 31(3), 239–249.

542

543 Thompson, M.M., 1966. Manual of Photogrammetry, 3rd ed. ASPRS, Virginia Falls.
544
545 Van Asselen, S., and A. C. Seijmonsbergen, 2006. Expert-driven semi-automated
546 geomorphological mapping for a mountainous area using a laser DTM, *Geomorphology*,
547 78(3-4), 309–320, doi:10.1016/j.geomorph.2006.01.037.
548
549 Wellner, J.S., Lowe, A.L., Shipp, S.S., Anderson, J.B., 2001. Distribution of glacial
550 geomorphic features on the Antarctic continental shelf and correlation with substrate:
551 implications for ice behavior. *Journal of Glaciology*, 47, 158, 397-411.
552
553 Wessel, P., Smith, W.H.F, 1998. New, improved version of Generic Mapping Tools released,
554 *EOS Trans. Amer. Geophys. U.*, 79 (47), 579.
555
556
557
558



561
562
563 **Fig 1:** a) Location of the study area. b) Drumlins (black) in the area as mapped by Smith et al
564 (2006). c) Recovery (i.e., 'completeness') as a function of size; synthesis of a manual
565 mapping pilot study for which the methodology was as here (see 'Interpretive Mapping') but
566 applied to 10 DEMs equivalent to Maps 1-5 using only one mapper (Armugam). Black line is
567 for height, H , and grey lines are for width W (solid) and length L (dashed). Circles are means
568 with their standard errors for the 10 DEMs, and dashed line is for medians. H , W , and L have
569 bin widths of 2.5, 25, and 100 m, respectively. At the upper end, bins with two or fewer input
570 data are omitted, giving maxima of 20, 275 and 800 m, respectively. All data are plotted
571 centrally within bins.

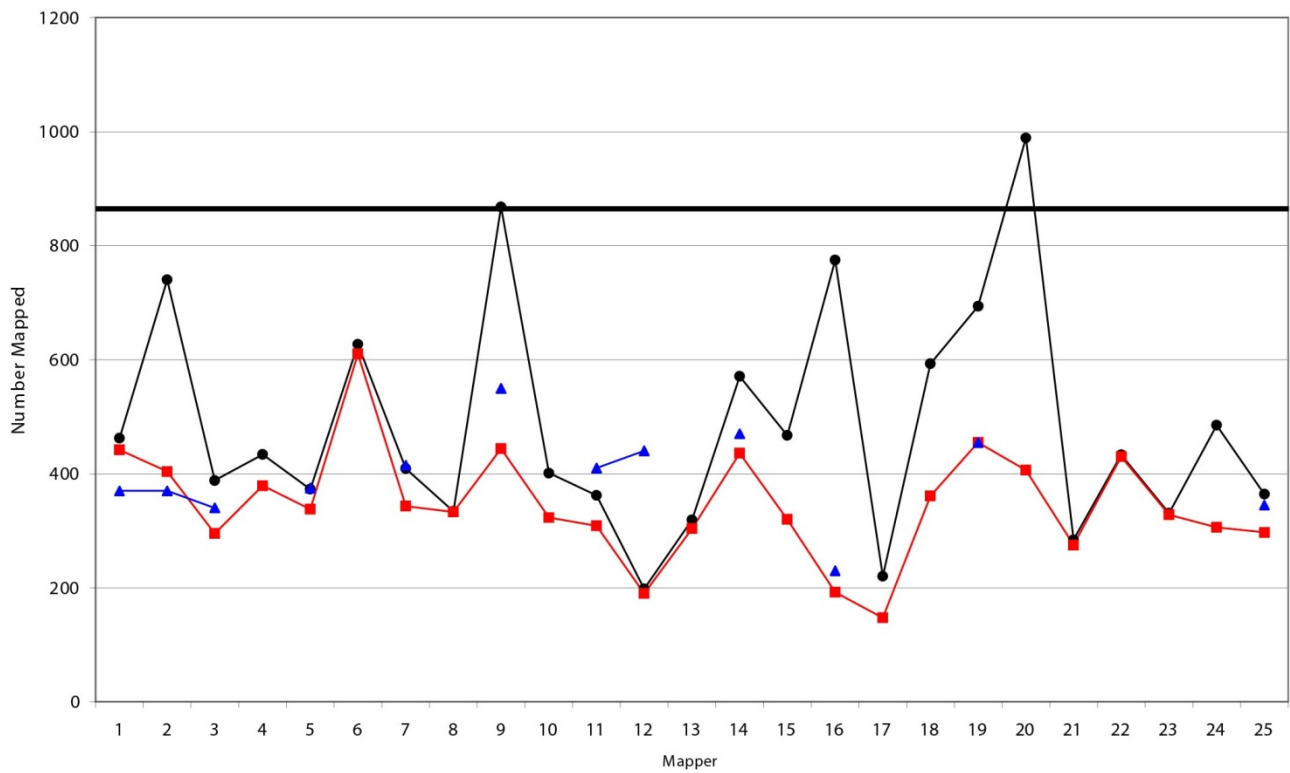


Fig. 2: Number of drumlins mapped per individual interpreter (black) and the number correct (red). Blue triangles are for the number correctly mapped in synthetic DEMs with parallel conformity, scaled (x5) to allow comparison. Horizontal black line is the number of drumlins in the synthetics. This was known to the mappers.